BELLCOMM, INC.

SUBJECT: Laser Guided Lunar Landing
Case 232

DATE: September 11, 1967

FROM: S.L. Penn

ABSTRACT

Post-Apollo lunar surface missions may include requirements for pin-point landings of unmanned supply vehicles. It is proposed to use a laser in the overflying CSM to irradiate the desired landing spot, providing a target for the landing vehicle to home on. Some of the more significant problems in defining a satisfactory laser guidance system are treated, a potentially useful system is evolved, and some alternatives and problems are indicated.

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MEMORANDUM FOR FILE

INTRODUCTION

In an advanced stage of lunar exploration, it may be necessary to land heavy logistics payloads in an unmanned Lunar Module. For efficient use of the payloads, it will be desirable to have the capability for a pin-point landing at a location chosen from orbital photography.

A system is proposed to use the crew in the CSM to identify and track the desired landing point through their guidance optics. A laser beam slaved to the guidance optics would illuminate the target, providing a bright spot for the unmanned lunar lander (LL) to home on. It is assumed (using Apollo parameters) that the CSM is at an altitude of 1.5×10^5 meters, moving at 10^5 meters/minute, so it can illuminate the desired spot for about 3 minutes, as it passes from $-45°$ to $+45°$ from the vertical. The CSM's ability to arrive over the landing site at the optimum time with respect to the LL's arrival is shown in Appendix A.

PROPOSED GUIDANCE SYSTEM

Referring to Fig. 1, the LL approaches the landing site at an angle of about 15° from the horizontal. It starts searching for the spot when it is about 10 NM (15×10^3 meters) out and moving at about 10 NM/min (but with velocity decreasing at about 1 NM/min/NM, to yield 0 at the site).

A laser beamspread $\theta = 2/3$ milliradian is selected, to irradiate a spot of diameter $D_i = 100$ meters on the lunar surface (for convenience, assume the spot is, or can be kept, essentially circular for incident angles from $-45°$ to $+45°$). The spot is kept from wandering by the CSM's manually controlled, coaligned telescope or an automatic image motion compensation device. Initially, it subtends a horizontal angle at the LL of

$\omega_{i_H} = \dfrac{100\ m}{15 \times 10^3 m} = 0.007$ radian $= 0.4°$ and a vertical angle

$\omega_{i_V} = \dfrac{100\ \mathrm{SIN}\ 15°\ m}{15 \times 10^3\ m} = 0.1°$. It is further assumed that

the receiver on the LL can be oriented so that its total field of view at the start of search would closely correspond to an ellipse centered on the landing point predicted by the guidance system and large enough to include the true landing point with high probability. For this first cut, we shall use the 90% confidence ellipse having dimensions of 4.88 Km in the direction of motion and 3.24 Km across[1]. If, for simplicity, we let this be 5 Km x 3 Km, the search area will subtend angles $\omega_{s_H} = \dfrac{3\ Km}{15\ Km} = 0.2$ radian $= 11.4°$ and $\omega_{s_V} =$

$\dfrac{5\ \mathrm{SIN}\ 15°\ Km}{15\ Km} = 0.09$ radian $= 5°$. The ratio of the projected

areas of the search area and the laser spot will be the ratio of the products of their projected major and minor axes or their subtended angles, i.e., $\dfrac{11.4 \times 5.0}{0.4 \times 0.1} = 1400$.

Searching could be performed in many different ways and would depend largely on the particular types of laser and detection scheme used. An evaluation of all possible or even several reasonable combinations is not practical for this first look. We shall try, for now, to find one satisfactory example of each and to indicate later what some of the other approaches might be.

Consider first a pulsed ruby laser operating in the Q-switched mode (for high peak power, short duration pulses) at a repetition rate determined by the time available for search, about 60 seconds (after 60 seconds the LL would be only about 3 NM from the center of the landing ellipse, satisfactory if scan began with the nearest part of the ellipse). A complementary search scheme might be to view one section of the search area at a time, moving to the next adjacent section each time the laser is pulsed until a signal is received. If the section viewed were the size of the laser spot, then up to 1400 such sections might have to be successively viewed before the irradiated spot was found. To scan a complete search area with 1400 separate looks in 60 seconds requires a laser repetition rate of $\frac{1400}{60}$ = 23 pulses per second. With ruby, this would be very hard to achieve while maintaining reasonable power output (about an order of magnitude beyond the state-of-the-art).

Another approach would be to use a ruby laser pulse rate of only 2.3 pps and to try to devise a scanning technique which could work with this slower rep rate. Background noise permitting (which we shall examine later), we might try expanding the instantaneous look area to ten times that of the laser spot and moving a correspondingly greater distance between looks. Now it would take only 140 separate looks to cover the entire search area. When the laser spot was thus approximately located, we would collapse the search field to that of the look area in which the spot had just been found and proceed to scan this new search field with a new look area the size of the laser spot. This should allow precisely locating the laser spot within ten more trials, or in a possible total of 150 trials. (In practice, the search and look angles would have to increase with time, as the LL would be getting closer to the landing ellipse with each succeeding pulse. Techniques for doing this and the possible difficulties therewith are not considered here.) The above rep rate is also predicated on the LL being able to recognize the laser spot when it first sees it and being able to adjust its course accordingly with as little as 3 NM to go. Otherwise, the rep rate or possibly the laser power output would have to be appropriately increased. These problems aside, however, the key question on which success of this technique depends is the adequacy of the intensity of the laser spot with respect to that of the solar illuminated lunar surface, i.e., the question of signal to noise.

SIGNAL TO NOISE CONSIDERATIONS

On the moon, the worst case for solar background competition with the laser would occur when the incident sunlight came from directly behind the receiver and parallel to its line of sight. The radiant intensity perpendicular to the beam of the solar flux at the lunar surface would be about 1000 watts/meter^2. The laser, at 2.3 pps, could be expected to emit pulses of 5×10^6 watts for durations of 30×10^{-9} seconds (for an overall efficiency of about 0.1%, input power required would be about 350 watts) with an intensity at the moon of 500 watts/meter^2. If the laser were directly above the target spot, the radiation reflected toward the receiver would be only 1/4 as intense as that directed back along the incident path. It would be as though laser radiation of 1/4 the actual intensity were illuminating the spot from the direction of the receiver, i.e., with 125 watts/meter^2. Hence the contribution to the receiver-observed spot brightness from the laser would be only 1/8 that from the sun, i.e, the laser irradiated spot would be 1/8 brighter than the surrounding surface. If, now, we include in the receiver a 10Å bandpass spectral filter centered at, and completely transmitting, 6943Å (the ruby laser output wavelength at 300°K) only 0.001 of the sun's radiation, the part within the spectral bandpass of the filter, would get through, and the laser spot would be 125 times brighter than the surroundings. Since the proposed look area would usually be ten times that of the laser spot, the effective gain, from the standpoint of the receiver, would only be 12.5.

To minimize the chance of a spurious noise pulse in the solar background giving us a false signal, at each laser pulsing we must take the precaution of leaving the receiver "on" for as short a time as possible commensurate with the laser pulse width and our uncertainties as to the distances and signal travel times involved. Synchronization of system operation would take place from the CSM. Appendix B examines the statistical basis for determining the likelihood of such a noise pulse occurring in the upto 150 "looks" that may be necessary, and provides the basis for confidence that a workable system can be devised, even in the worst backscatter case.

OTHER TECHNIQUES

The above scheme is presented as a feasibility argument rather than an attempt at optimization. In any more complete study of the laser homing problem, the possibility of finding a more effective laser source and receiver/detector combination than discussed here should be evaluated. Other laser candidates offering a variety of combinations of reliability, efficiency, and spectral and power outputs are: neodymium doped crystal and glass lasers, liquid lasers, argon lasers, CO_2 lasers, and semi-conductor lasers. Continuous vs pulsed operation should be also be evaluated.

Some candidate detection schemes are:

(a) Scan the search area with a receiver beam width that just covers the laser spot size (considered, but not adopted in the present treatment due to low rep rate capability of ruby),

(b) Scan with a receiver beam width that is intermediate between the overall area of concern and the desired spot, then, when the spot is localized to a smaller area, adjust beam down and scan the smaller area (as adopted herein),

(c) Have beam wide enough to encompass the entire search area and now electronically scan the receiver tube for the spot image (photomultiplier image dissector), and

(d) Use lateral photocell, which locates the angular displacement of a light source from the optic axis of the cell by photovoltic type responses proportional to the image displacement.

Other detectors than phototubes might also be worth looking at, e.g., silicon semiconductor diodes.

For purposes of illustration, operation in modes (a) and (c) is depicted in simplified form in Fig. 2. Assuming 1.4 inch diameter phototubes for each mode, (a) could have a movable mask with an elliptical aperture of 0.05 x 0.012 inches. In conjunction with this aperture, a lens of 7 inch focal length would provide the 0.4° x 0.1° field of view required by the laser spot size. Mechanical motion of the mask to move the aperture over an appropriate elliptical section of the phototube face would enable the receiver to scan the 11.4° x 5° search angle. In mode (c), the image dissector would only accept electrons coming from a 0.05 x 0.012 inch section of the photocathode selected by the electric or magnetic field and an appropriate sized, fixed internal aperture. Again, a 7 inch focal length lens would provide the image of the laser spot. The search angle would be scanned by varying the field between the deflection plates. This technique has the particular advantage of very low dark noise, since only a small portion of the tube face is seen at one time.

CONCLUSIONS

The problem of terminal guidance of an automated lunar landing vehicle to a laser illuminated landing spot has been considered. It has been shown how one possible laser-detector scheme might work. This should not be regarded as the optimum configuration, though, since many other combinations are possible. Additional room for improvement is seen through optimization of electronics, reduction of gate time, and constraint of landing to more favorable lighting conditions, possibly even in earth shine.

ACKNOWLEDGEMENT

I wish to thank C.J. Byrne for providing the problem and for the treatment of the timing considerations given in Appendix A, F.G. Allen for his assistance in the statistical analysis of the noise in Appendix B, and both these gentlemen for their many other helpful comments and reviews.

S. L. Penn

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Attachment
Appendix A
Appendix B

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REFERENCES

1. "Lunar Landing Site Selection Briefing", MSC, Mar. 8, 1967
2. "Apollo Lunar Landing Mission Symposium", Vol I, MSC, June 25-27, 1966
3. Handbook of Probability and Statistics, with Tables, Burington and May, 1958

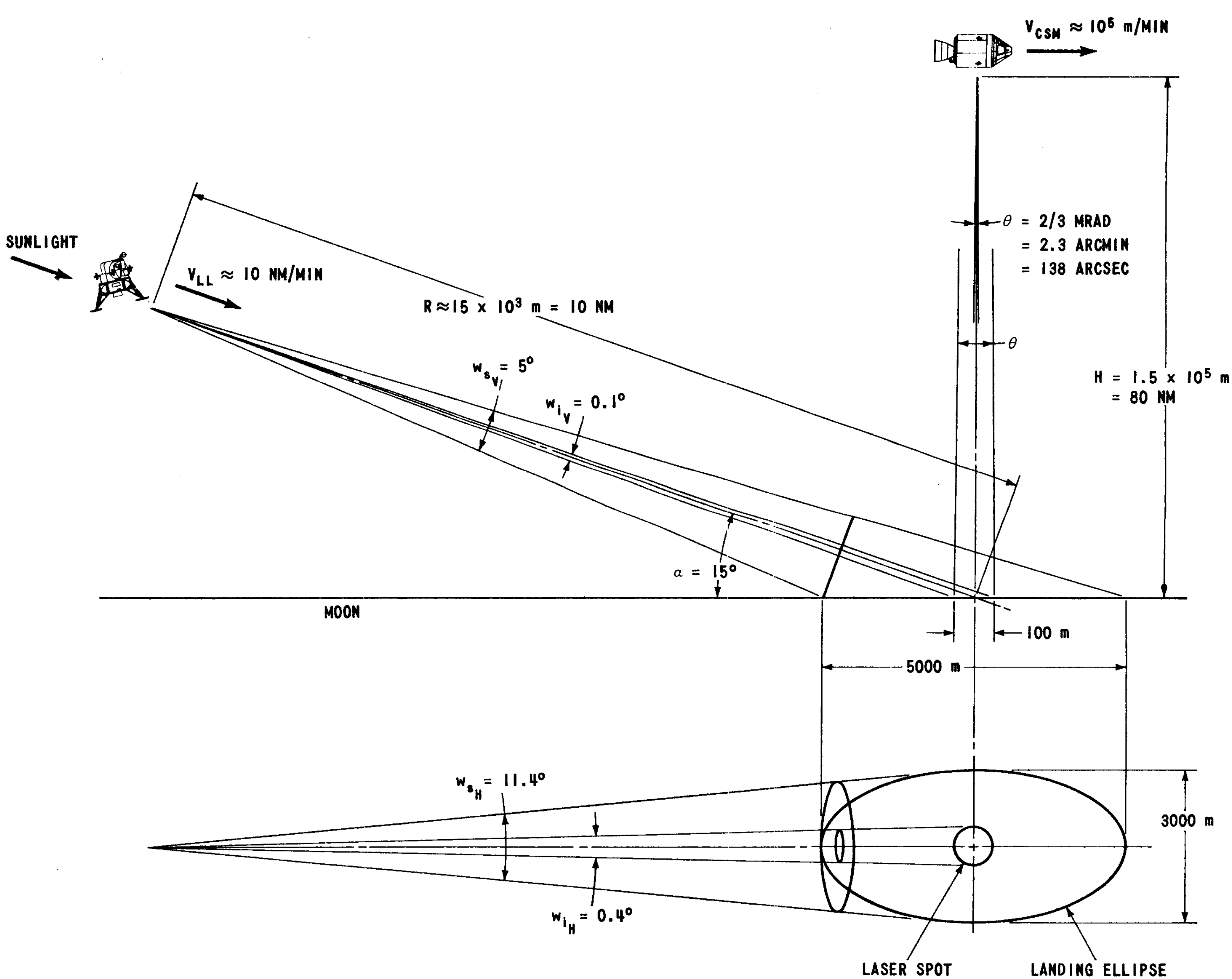


FIGURE 1 - LASER HOMING PROBLEM (NOT TO SCALE)

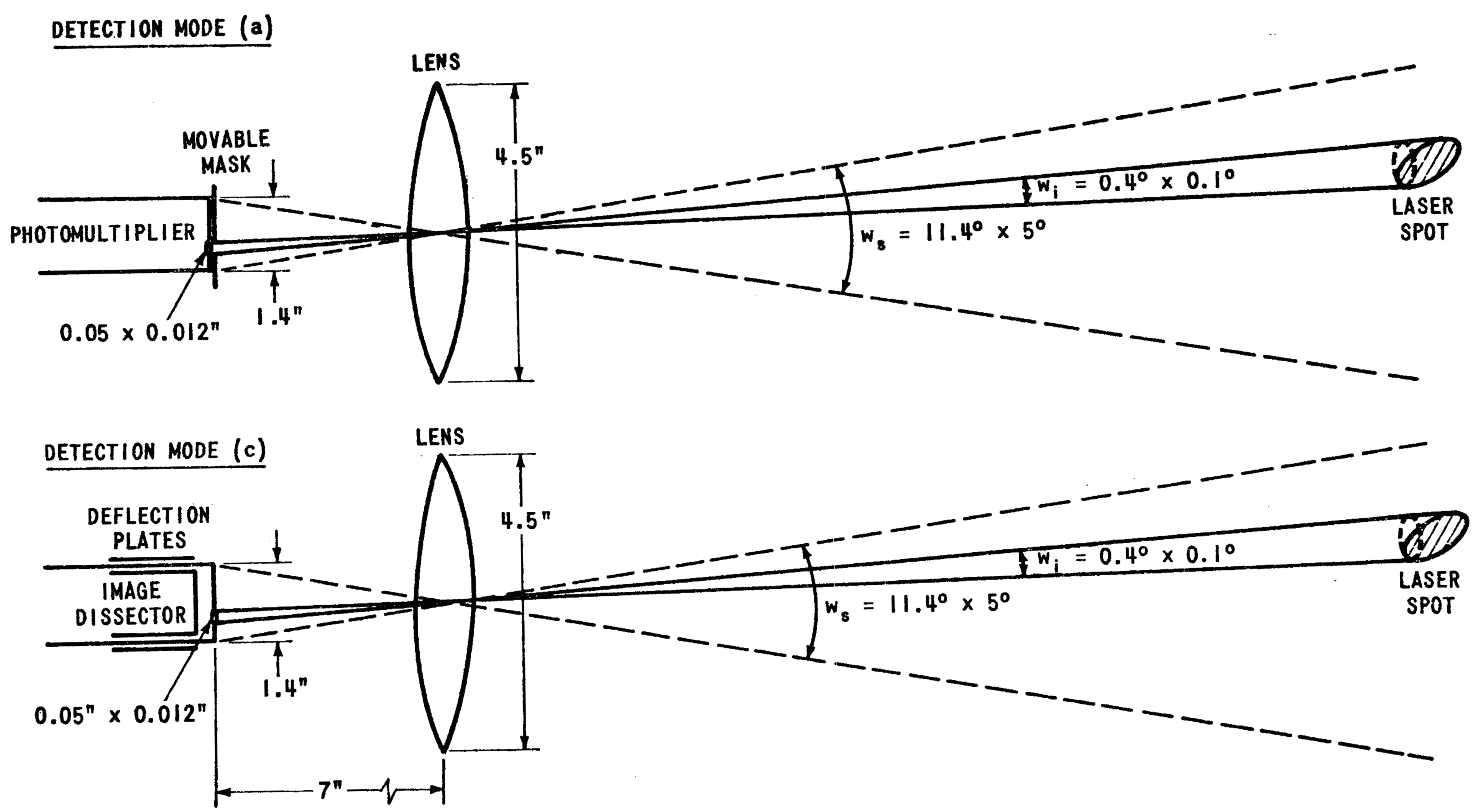
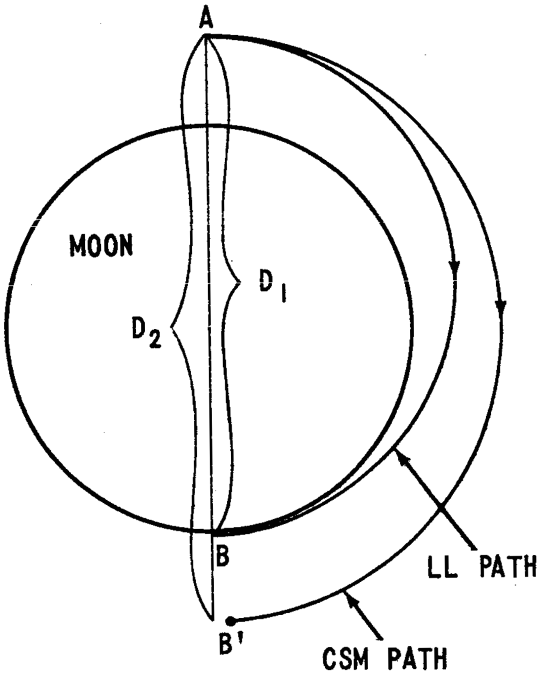


FIGURE 2 - TWO CANDIDATE DETECTION SCHEMES (NOT TO SCALE)

APPENDIX A

TIMING OF CSM AND LL ARRIVALS

A key question is whether the CSM will really be overhead at the landing spot at the right time to enable the laser homing operation to proceed. To see that it is, consider the following argument, while referring to the sketches:



Keplers 3rd law states that planetary orbital periods vary as the 3/2 power of the orbital radii, i.e., $T = kR^{3/2}$ (1)

To find the time difference for a CSM to go from A to B' while the LL goes $\sim$ 180° from A to B (approx. point of engine ignition for powered descent), differentiate (1) and get

$$\Delta T = \frac{3}{2} k R^{1/2} \Delta R \qquad (2)$$

Divide by (1) (to eliminate k) and get

$$\frac{\Delta T}{T} = \frac{3}{2} \frac{\Delta R}{R} \qquad (3)$$

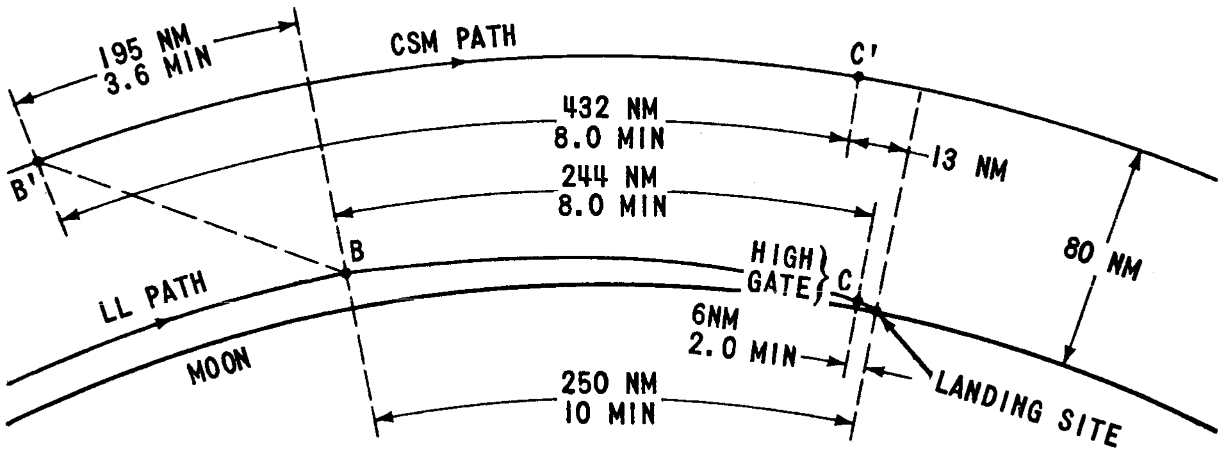
For R $\approx$ 1000 miles, $\Delta R = 1/2\ \Delta D = 40$ miles, and

$$T \approx 1 \text{ hr} = 60 \text{ minutes},$$

We have

$$\Delta T = \frac{3}{2} \times \frac{\Delta R}{R} T = \frac{3}{2} \times \frac{40}{1000} \times 60$$

$$= 3.6 \text{ minutes}$$



At engine ignition point B, the LL is flying almost parallel to the surface. It has approximately 250 nautical miles and 10 minutes to go to touchdown.* The CSM, as we have seen, is about 3.6 minutes behind, or 195 NM at its velocity of 54 NM/min. 8 minutes later the LL arrives at High Gate, C, about 6 NM from the landing site, and the CSM is 13 NM short of the landing site. The position of the CSM relative to the landing site can be shifted precisely, as needed, to meet the requirements for spot irradiation time, by adding or subtracting a little ΔV when the LL Hohmann transfer is initiated, e.g., adding sufficient ΔV (about 13 FPS) to raise the CSM's orbit from 80 to 90 NM in the vicinity of the landing site would retard the CSM with respect to the LL by an additional $\frac{10}{80} \times 195 = 24$ miles, so it would still have 37 NM to go when the LL was at High Gate instead of 13 NM.

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*Distances and times used here are approximations from data presented for the LM on Apollo missions in References 1 and 2.

APPENDIX B

SIGNAL VS NOISE

The extent to which the solar background might be expected to interfere with the laser signal is determined as follows:

Let P_s be the radiation in watts incident on the detector due to the solar illumination of the moon in the field of view. It can be shown that

$$P_s = \tau B \ \Omega A \tag{1}$$

where

τ is the fraction of the sun's radiation lying within the bandpass frequencies of the receiver filter (for simplicity, it is assumed that there is 100% transmission within the bandpass and none without)

$= 0.001$ (10 Å filter at 6943 Å)

B is the radiance (power/unit projected area of the moon in the field of view/unit solid angle) of the reflected sunlight at the LL (to be computed)

Ω is the solid angle subtended by the area of the moon in the field of view as seen from the LL (to be computed)

A is the area of the receiver lens

$= 100 \text{ cm}^2$ (assumed)

$$B = \frac{E}{\pi} \rho \ \phi \tag{2}$$

where

E is the solar constant at the mean distance of the earth from the sun

$= 10^3$ watt/meter^{2*} $= 10^{-1}$ w/cm^2

ρ is the local albedo of the moon

$= 0.06$ (actually, $0.06 \lesssim \rho \lesssim 0.18$. Since albedo affects laser light and sunlight the same, lowest value of ρ is chosen to give worst possible statistics)

ϕ is the photometric function of the moon in the direction of concern

$= 1$ (worst case)

Making the appropriate substitutions in Eq. (2) we have

$$B = 0.002 \text{ w/cm}^2\text{/steradian}$$

For up to 140 pulses, Ω would be ten times the solid angle subtended by the laser spot (see main text for explanation), so (for small angles)

$$\Omega = 10 \frac{\pi}{4} \omega_{i_H} \omega_{i_V} = \frac{30}{4} \times (7 \times 10^{-3}) \times (1.75 \times 10^{-3})$$

$$= 90 \times 10^{-6} \text{ steradian}$$

Now, with all the factors from the right side of Eq. (1) determined, we get

$$P_s = 180 \times 10^{-10} \text{ watts}$$

In terms of photons at 6943 Å,

$$P_s = \frac{180 \times 10^{-10} \text{ joules/sec}}{2.8 \times 10^{-19} \text{ joules/photon}}$$

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*Actually 1.3×10^3 watt/meter^2, but approximation is consistent with the uncertainty in the laser power.

$$= 60 \times 10^9 \text{ photons/sec}$$

$$= 60 \text{ photons/nanosec}$$

Assuming a quantum efficiency for the detector of about 5% (RCA 4526 photomultiplier)*, in terms of photoelectrons generated at the photocathode

$$P_s = 3.0 \text{ photoelectron/nanosec.}$$

In a time equal to the laser pulse width (30 nanosec)

$$P_{s_{30}} = 90 \text{ photoelectrons}$$

The laser spot, while 125 times as bright as terrain illuminated by the sun (over the 10Å bandpass of the filter), produces a signal only 12.5 times as intense (again, see main text) or 1125 photoelectrons/pulse.

A first guess at a practical receiver gate width is 1μ sec (on-time for looking for the laser signal; requires continual knowledge of the difference in the distances from the CSM to the LL via the laser spot and from the CSM direct to the LL to an accuracy of about 1000 ft and ability to adjust gate onset accordingly). If we assume, as a worst case, a receiver that compares, gate by gate, the total photoelectric output per gate, then 3000 electrons/gate (ignoring the detector multiplication process) will be the average background level, which we shall define as noise, and 3000 + 1125 = 4125 electrons the average signal plus noise when occurring together.

The 4 σ fluctuations of both the noise and the signal plus noise will now be examined, since in each case there is only a 0.00003 probability of deviations from the average in any one direction exceeding these values[3].

For the noise, $1\,\sigma = \sqrt{3000} = 55$

$$4\,\sigma = 220 \text{ electrons}$$

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*And also assuming that dark current (thermally dependent emission, which would exist with even no incident radiation) can be kept negligible.

For the signal plus noise, $1\sigma = \sqrt{4125} = 64$

$4\sigma = 256$ electrons

If the receiver decision mechanism can be set, in this case, to reject any accumulation of up to 3220 photoelectrons and to accept every accumulation of over 3869 photoelectrons (or other appropriate values for different ρ's and ϕ's, simple enough where ρ and ϕ are not expected to vary), then the chance, in 140 trials, of getting either a false signal or no signal when one is present is no more than 2 x 140 x 0.00003 = 0.008. The up to 10 additional trials possibly needed for final spot location would be at still higher signal to noise ratio than the first 140 because we would then be looking at sections of the lunar surface equal in size to the laser spot and be getting the full advantage of the laser brightness superiority. Following an argument similar to the above, one could show these 10 trials to contribute an insignificant change to the probability of making a wrong decision.

Gradual changes of $\rho\phi$ can probably be compensated for by building into the system a capacity for continuous brightness level measurement as the landing site is approached and appropriate, pre-planned self adjustment of the decision levels. While the liklihood of sharp changes in brightness level over the anticipated fields of view and landing terrain is believed small, further evaluation of the possibility of such sharp changes and of the feasibility of effective countermeasures should be undertaken.

It should also be clear that landings under other lighting conditions (different sun angles or, possibly, even in earth shine) than the worst backscatter case is a likely and beneficial expectation.

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